POLARIZED-ELECTRON — POLARIZED-ATOM SCATTERING

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Collisions between electrons and atoms, ions, or molecules are among the most basic of all physical processes. Such collisions determine the detailed behavior of a wide spectrum of physical phenomena, ranging from electrical resistivity, to gaseous discharges, energy transport in plasmas, and chemistry in the earth's and stellar atmospheres. A correct understanding of all such processes requires an accurate and detailed characterization of the underlying electronic collisions. Further, accurate theoretical modeling of electron transport in all such processes is critically dependent both on the theoretical description of electron collision events and on the availability of reliable electron scattering cross sections. Because it will likely never be possible to determine experimentally all of the scattering cross sections required for the modeling of the full range of scattering processes, it will always be necessary to rely on theoretical electron scattering calculations for the vast majority of the electron scattering data.

Unfortunately, theoretical techniques have not yet progressed to the point that one can reliably produce accurate electron scattering cross sections for the full range of possible scattering targets and scattering energies. At sufficiently high impact energy, where the details of target structure are relatively less important and where the Born approximation may be reasonably accurate, many cross sections are reasonably well calculated. At sufficiently low impact energies, where only a few target states contribute significantly to the collision process, *ab initio* close-coupling calculations are generally expected to provide close agreement between theory and experiment. However, collisions at intermediate energies, from about the threshold for inelastic excitation up to several times the ionization potential, still provide a substantial challenge for theoretical model calculations. Because the cross sections for many important scattering processes reach their maximum value in this energy range, it is essential that theoretical techniques be developed with which to produce reliable electron scattering cross sections.

Collision studies which make use of quantum state preparation and detection techniques have led to a considerable advance in our knowledge of scattering phenomena. In the particular case of electron–atom collisions, substantial progress in the use of coherence, correlation, coincidence, polarization, optical pumping, and step-wise excitation techniques has made possible experimental investigations which are increasingly detailed in their characterization of scattering processes[1–8]. The ultimate goal of such measurements has been the "complete" or "perfect" experiments envisioned by Bederson[9] in which all quantum observables are determined. Through measurements which make use of techniques of quantum state preparation and state detection, one is provided with the most detailed and complete characterization possible of the interactions at work in, and the scattering dynamics of, collisions between electrons and atoms.

In our laboratory in the Electron Physics Group at the National Institute of Standards and Technology in Gaithersburg, MD, we have undertaken an experimental program utilizing electron and atom spin-polarization techniques in order to study the role played by spin in low energy collisions between electrons and atoms. In particular, we are interested in making "complete" measurements for the effects of exchange in elastic and inelastic electron–atom scattering. One great advantage of our method is that for each incident energy, we can make very detailed measurements of the spin dependence in both the elastic and the dominant inelastic scattering channel.

There are two fundamental causes of spin dependence in electron-atom collisions, namely exchange and the spin-orbit interaction[5]. The spin-orbit interaction arises from the interaction of the magnetic moment (spin) of an electron with the magnetic field felt in the rest frame of that electron because of its motion in the electric field of the scattering target. The effective magnetic field is always perpendicular to the scattering plane determined by the momentum of the electron before and after collision. As a result of this effective magnetic field, electrons at a given impact parameter whose spins are "up" relative to the scattering plane have a different energy from electrons whose spins are "down". Hence, the scattering cross section for "up" electrons is different from that for "down" electrons. Such scattering is generally referred to as Mott scattering and serves as the basis for essentially all electron spin detectors. Collisional effects arising due to the spin-orbit interaction have been the subject of extensive study and have led to significant improvement in our understanding of collisional processes[5,6]. However, because the primary interest of our work is the other fundamental source of spin dependence, exchange, the collisional effects of the spin-orbit interaction will not be further discussed here.

Exchange differs from the spin-orbit interaction in that it is not the result of any spin-dependent force at work during the scattering, but is a manifestation of inherent symmetry properties of the wavefunctions of spin-$\frac{1}{2}$ particles. The simplest system in which to introduce the most important ideas necessary for the understanding of exchange in electron–atom scattering is elastic scattering of spin-polarized electrons from a spin-polarized one-electron atom such as hydrogen, or equivalently, an alkali

atom. The ideas we develop are readily applicable to inelastic collisions as well. As we will see, exchange introduces a dependence of the scattering cross section for such systems on the relative orientation of the spins of the incident electrons and atoms. As a result, a measurement of this spin dependence gives one a direct measure of the role played by exchange in these collisions.

In the absence of any spin-orbit interaction, only three non-equivalent scattering scenarios are possible for elastic collisions between spin-polarized electrons and spin-polarized atoms:

$$e(\uparrow) + A(\downarrow) \rightarrow e(\uparrow) + A(\downarrow) \tag{1}$$
$$e(\uparrow) + A(\downarrow) \rightarrow e(\downarrow) + A(\uparrow) \tag{2}$$
$$e(\uparrow) + A(\uparrow) \rightarrow e(\uparrow) + A(\uparrow) \tag{3}$$

Here, the up and down arrows indicate the direction of the electron's and atom's spin polarization relative to some fixed axis.

In the first example, the spins of both particles remain unchanged, so one can say that no "exchange" has occurred, and the scattering is characterized by a "direct" scattering amplitude, conventionally denoted by f. In the second example, both spins have changed, so "exchange" has clearly taken place, and the scattering is characterized by an "exchange" amplitude, generally denoted by $-g$. In the third process, one cannot tell whether the electrons have "exchanged" or not, so both channels contribute and the scattering is described by the amplitude $f - g$, which involves interference between "direct" and "exchange" scattering.

There are several important points to notice from this description. First, the complete description of this simple scattering process requires two, and only two, scattering amplitudes, f and g. Second, these scattering amplitudes are complex, so that one must determine both their magnitude and their relative phase. Finally, if one wishes to determine anything about the separate contributions of the "direct" and "exchange" channels to the total scattering, one must be able to control or detect the spin state of at least two projectiles. Nothing would be learned about the difference between f and g, for example, from a measurement only of the spin polarization of the scattered electron if one averaged over the spin orientation of both the incident electron and atom. However, if one scatters "up" polarized electrons from unpolarized atoms and detects only "down" polarized electrons, for example, then only the "exchange" amplitude g contributes to the scattering intensity and its magnitude can be determined independently of the "direct" amplitude, f.

While there is a certain attraction to the previous description of scattering in terms of "direct" and "exchange" events, it is advantageous to adopt an alternative description which more clearly reflects one of the most important symmetries of the scattering process, namely that the total spin of the system, electron plus atom, is

conserved during the collision. The total spin conservation is emphasized by treating the spin of the colliding electron and atom pair as coupled to form either a singlet or triplet spin state, which is unchanged by the collision. Collisions which take place in either the singlet or triplet state are then fully described by independent singlet and triplet complex scattering amplitudes, S and T, respectively. These amplitudes are related to the f and g by

$$S = f + g \tag{4}$$
$$T = f - g \tag{5}$$

respectively.

A complete characterization of this scattering process requires the determination of three parameters, e.g. the magnitudes of S and T and the phase difference between them. Because the cross sections for scattering in the singlet or triplet channel are simply proportional to the squared magnitudes of the amplitudes, those magnitudes can in principle be determined from a measurement of the singlet and triplet scattering cross sections. In terms of these singlet and triplet scattering cross sections, the conventional spin unpolarized cross section, which we denote by σ_{tot}, is given by

$$\sigma_{tot} = \frac{1}{4}(\sigma_S + 3\sigma_T). \tag{6}$$

The scattering process described in Eq. (3) is a realization of the pure triplet state experiment. Because the initial spins are parallel, only the triplet state is represented and the scattering signal $I_{\uparrow\uparrow}$ is simply proportional to the triplet scattering cross section. That is, $I_{\uparrow\uparrow} \propto \sigma_T = |T|^2$. An absolute determination of that scattering cross section is thus sufficient for a determination of the magnitude of the triplet complex scattering amplitude.

In this and all following discussion, we specifically assume that both the electrons and atoms are completely polarized and ignore completely any complications which arise from the incomplete polarization exhibited by all realizable beams. One can fully account for the effects of the incomplete polarization of real experiments in a rather straightforward manner, without affecting in any significant way either our analysis or the conclusions one draws from our experimental results[5,10].

Unfortunately, the singlet channel cannot be studied quite as readily as the triplet channel. The antiparallel incident spin configurations illustrated in Eq. (1) and Eq. (2) above must be described as linear combinations of singlet and triple spin states, so that the two scattering scenarios are described by amplitudes which are linear combinations, $(S \pm T)$, of the singlet and triplet complex scattering amplitudes . The scattering cross sections for these two processes would be

$$|S|^2 + |T|^2 \pm 2|S||T|\cos(\phi_{ST}) \tag{7}$$

where ϕ_{ST} is the relative phase difference between S and T. If no analysis is performed of the spin of the scattered electrons, then one cannot distinguish between

these processes and the cross section for scattering in the initially antiparallel relative spin orientation is just the average of the two cross sections, so that

$$\sigma_{\uparrow\downarrow} = \frac{1}{2}(\sigma_S + \sigma_T). \tag{8}$$

Notice that there is no sensitivity in either $\sigma_{\uparrow\uparrow}$ or $\sigma_{\uparrow\downarrow}$ to "interference" between singlet and triplet scattering, and hence no information about the relative phase between S and T. In order to determine that phase difference, one would need to determine the change in spin polarization of either the electron or atom during the collision. Such experiments, being extremely difficult, have not yet been performed and will not be discussed further.

Because we are primarily interested in the role of exchange during these collisions, we choose to concentrate not on absolute measurements of the scattering cross sections $\sigma_{\uparrow\uparrow}$ and $\sigma_{\uparrow\downarrow}$ themselves, but on how these cross sections are affected by exchange. We define an exchange asymmetry, A_{ex}, as the difference between scattering in the initially antiparallel versus initially parallel relative spin orientation, normalized to their sum. That is,

$$A_{ex} = \frac{\sigma_{\uparrow\downarrow} - \sigma_{\uparrow\uparrow}}{\sigma_{\uparrow\downarrow} + \sigma_{\uparrow\uparrow}} = \frac{\sigma_S - \sigma_T}{\sigma_S + 3\sigma_T}. \tag{9}$$

This exchange asymmetry is directly related to the ratio, r, between the triplet and singlet scattering cross sections by

$$r = \frac{\sigma_T}{\sigma_S} = \frac{1 - A_{ex}}{1 + 3A_{ex}}. \tag{10}$$

In the limit of a vanishing triplet scattering cross section, A_{ex} takes on a value of $+1$ and r is zero. If, however, it is the singlet cross section that becomes very small, then A_{ex} takes a value of $-\frac{1}{3}$ and r approaches infinity. If exchange plays a negligibly small role in the collision, then S and T are identically equal so that A_{ex} vanishes and $\sigma_S = \sigma_T$ so that r is unity.

Because the triplet/singlet cross section ratio, or equivalently the exchange spin asymmetry, measures how σ_S and σ_T differ from the spin unpolarized cross section, σ_{tot}, a measurement of either A_{ex} or r, along with an absolute measurement of σ_{tot}, is sufficient for a determination of both $|S|$ and $|T|$.

One important advantage of measuring relative quantities, such as the exchange asymmetry or the cross section ratio, is that one can extract directly from the experimental observations specific information about a specific effect, in this case exchange, without suffering from the numerous systematic problems which plague accurate measurements of absolute scattering cross sections.

We now turn to a discussion of inelastic scattering processes, first considering how one would describe excitation processes if electrons had no spin. We concentrate

on electron induced transitions between S and P states. Because the P state has three degenerate magnetic sublevels, a complete description of this excitation requires, in principle, three complex scattering amplitudes, one for exciting the single S state to each magnetic sublevel of the P state. For the case of $S \rightarrow P$ excitations, and ignoring any influence of the spin-orbit interaction, one can use symmetry considerations to reduce the number of amplitudes. Because the scattering process must preserve the overall positive reflection symmetry about the scattering plane defined by the momentum of the incident and scattered electrons, any angular momentum transferred to the atom must be perpendicular to this plane. We therefore choose to describe the collision in a coordinate system in which the atomic orbital angular momentum is quantized along an axis perpendicular to the scattering plane. In this coordinate system, the amplitude for exciting the $M_L = 0$ magnetic sublevel must vanish. One is thus left with two complex amplitudes, $F_{\pm 1}$, for excitation of the $M_L = \pm 1$ sublevels, respectively.

These amplitudes, including their relative phase, can be determined in an appropriate study of electron impact excitation. Suppose a collision event excites an atom initially in the ground state to the $M_L = +1$ excited state. That excited atom will subsequently emit a photon which, if detected along the direction normal to the scattering plane, has pure circular polarization. Atoms excited to the $M_L = -1$ sublevel would show the opposite circular polarization along the same direction. Thus, a measurement of the circular polarization of the photons emitted normal to the scattering plane, in coincidence with the electron which excited the atom, gives a direct measure of the relative magnitudes of F_{+1} and F_{-1}.

Similar to the approach taken for elastic exchange scattering, we define a relative quantity to characterize the difference between F_{+1} and F_{-1}:

$$L_\perp = \frac{\sigma_{+1} - \sigma_{-1}}{\sigma_{+1} + \sigma_{-1}} = \frac{|F_{+1}|^2 - |F_{-1}|^2}{|F_{+1}|^2 + |F_{-1}|^2}. \tag{11}$$

The symbol $L_\perp$ is chosen because the measured quantity can be simply interpreted as the net angular momentum, perpendicular to the scattering plane, which is transferred to the atom on excitation to the P level[2].

Of course, collisions seldom leave the excited atoms in a pure $M_L = +1$ or $M_L = -1$ state. The excited states generally have contributions from both $M_L = +1$ and $M_L = -1$ magnetic sublevels, with their relative contributions determined by the magnitudes of $F_{\pm 1}$. Therefore, the light emitted normal to the scattering plane, having a coherent superposition of both + and − circularly polarized components, has a linearly polarized component as well. The direction of this linear polarization is uniquely determined by the phase difference between the excitation amplitudes. Consequently, a determination of that linear polarization direction, again in coincidence with the scattered electron, is sufficient to determine this phase difference[2].

Rather than perform the experiments as just described using electron-photon coincidence techniques, it is advantageous to perform so-called *superelastic* scattering measurements wherein one first photo-excites the atomic target and then measures the

cross section for electron impact de-excitation of the excited target[11]. Because the measurement process itself ensures detection only of electrons which have gained the excitation energy of the atoms, and hence are known to have de-excited an excited atom back to the ground state, coincidence techniques are not required. In effect, coincidences between the photon and scattering electron are enforced from the outset, with a subsequent substantial increase in scattering signal. Time reversal symmetry assures us that the measured quantities are identical to those measured with electron–photon coincidence techniques. From the cross section for de-exciting atoms prepared with + and − circularly polarized light, one determines $L_\perp$. From the dependence of the scattering signal on the polarization angle of linearly polarized light, one determines the relative phase between the excitation amplitudes.

The above description would be complete for $S \rightarrow P$ excitation if electrons had no spin. We now look to what needs to be changed to incorporate spin into the picture. Basically, we need to allow for the excitation of each magnetic sublevel through the independent singlet or triplet spin channels. That is, rather than two complex amplitudes, $F_{\pm 1}$, we require four, $S_{\pm 1}$ and $T_{\pm 1}$, for excitation of the $M_L = \pm 1$ sublevels via the singlet or triplet scattering channels, respectively.

To completely determine four complex scattering amplitudes, to within an arbitrary overall phase, one needs seven real parameters, four to characterize the magnitudes of the scattering amplitudes, and three to characterize three relative phases. Because experiments have not yet been developed to cleanly determine the relative phase differences, we will not discuss them further[10]. As for the magnitudes, it is convenient to choose the conventional excitation cross section, which we have called σ_{tot}, for scattering which is averaged over spin and orbital angular momentum, and three relative quantities which describe physical aspects of the collision.

We can define the angular momentum transferred perpendicular to the scattering plane in a way similar to that for excitation without spin, but now resolved into singlet and triplet channels:

$$L_\perp^S = \frac{|S_{+1}|^2 - |S_{1-}|^2}{|S_{+1}|^2 + |S_{-1}|^2} \tag{12}$$

and

$$L_\perp^T = \frac{|T_{+1}|^2 - |T_{-1}|^2}{|T_{+1}|^2 + |T_{-1}|^2}. \tag{13}$$

For the final relative quantity we again choose the ratio of triplet to singlet scattering, but now averaged over angular momentum transferred:

$$r = \frac{\sigma_T}{\sigma_S} = \frac{(|S_{+1}|^2 + |S_{-1}|^2) - (|T_{+1}|^2 + |T_{-1}|^2)}{(|S_{+1}|^2 + |S_{-1}|^2) + 3\,(|T_{+1}|^2 + |T_{-1}|^2)} \tag{14}$$

These relative quantities are constructed from various combinations of the scattering signals from the four possible relative orientations of the electron and atom orientations. The details for constructing these quantities from the experimental signals are given elsewhere and will not be repeated here[10,12].

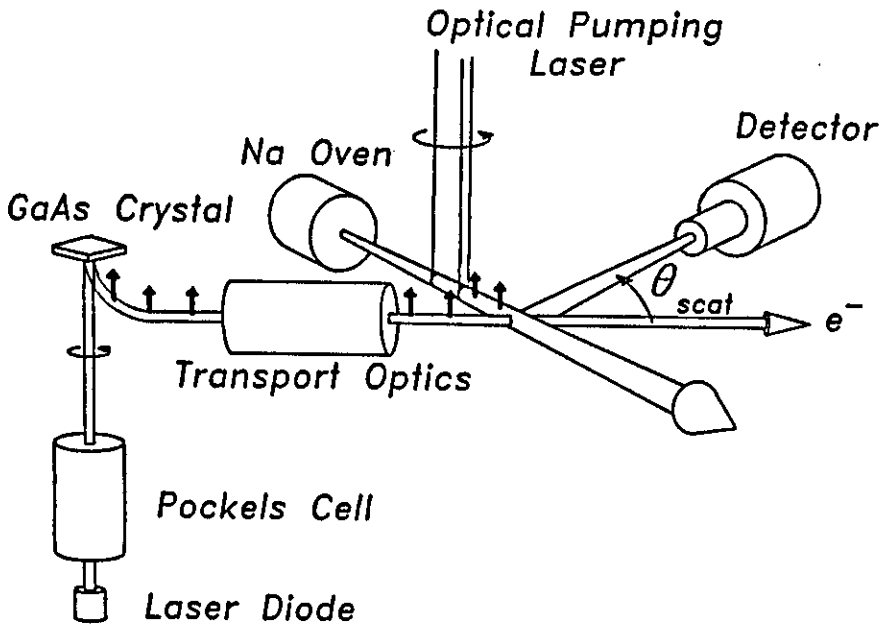

Fig. 1. Schematic drawing of the polarized electron–polarized atom scattering apparatus.

To illustrate the ideas developed for understanding spin dependence in elastic and inelastic scattering, let us now consider the results of our measurements of spin dependence in elastic and inelastic scattering of spin-polarized electrons from optically pumped sodium atoms. The experimental procedure has been described in detail elsewhere[12] so only a brief description is necessary here.

The experimental apparatus, shown schematically in Fig. 1, consists of crossed beams of electrons and sodium atoms. The electrons are produced by photoemission from a GaAs crystal photocathode[13] using light from a GaAlAs diode laser operating at a wavelength of 810 nm. The laser light is circularly polarized with the helicity determined by the polarity of the voltage applied to a Pockels cell. The photoemitted electrons have a net spin polarization of about 29% which is either normal or antinormal to the crystal surface, depending on the helicity of the incident laser light. The emitted electrons are collected and deflected by 90° to form a beam with transverse spin polarization, either up or down in the laboratory. This beam is variable in energy from about 2 to 100 eV and is focused at the scattering center with a nominal spot size of about 2 mm.

Sodium atoms from a continuously recirculating, effusive oven are collimated to form a beam with a diameter of about 4 mm at the scattering center. The atomic density is about 5×10^9 atoms/cm^3 under normal operating conditions. The atoms

are prepared by optical pumping with light from a single-frequency dye laser tuned to the $3^2S_{\frac{1}{2}}(F=2) \rightarrow 3^2P_{\frac{3}{2}}(F=3)$ hyperfine transition[11]. The polarization direction, again either up or down in the laboratory, is determined by the helicity of the circularly polarized optical pumping light. For elastic scattering measurements, the optical pumping takes place just slightly upstream in the atomic beam from the interaction region so that only ground state atoms are present in the scattering center. The net spin polarization of the ground state atomic target is about 60%. For the superelastic measurements, the optical pumping takes place directly in the interaction region. A steady-state population of excited atoms, approximately 30% of the total number of atoms, is maintained by the optical pumping. The excited atoms are essentially 100% spin polarized and also maintained in pure magnetic sublevels with $M_L = +1$ or -1, depending on the helicity of the pumping light.

Electrons scattered through some angle θ_{scat} are collected at the detector which is rotatable about the scattering center and can measure scattering in the range from about 15° to 140°. The detector includes a retarding field energy analyzer in order to discriminate against inelastically scattered electrons for the elastic scattering measurements, and against both inelastically and elastically scattered electrons for the superelastic measurements. For both the elastic and superelastic measurements, scattering signals are accumulated for each of the four possible relative spin orientations of the incident electrons and atoms. From these four scattering signals we construct the relative quantities which show the role played by electron spin as discussed above.

Fig. 2 shows results of our measurements of these quantities for spin-polarized superelastic scattering from the $3P$ excited state of sodium at the relatively low incident energy of 2.0 eV. This corresponds to an incident energy of 4.1 eV in the equivalent inelastic scattering process. Measurements of spin dependence in elastic scattering at this low incident energy are not yet available.

In Fig. 2(b) our experimental results for $L_\perp^S$ and $L_\perp^T$ are shown. The results for the ratio, r, are shown in Fig. 2(c). Additionally, the unpolarized $L_\perp$ is shown in Fig. 2(a), along with the experimental results of Hermann *et al.*[14] at 3 eV incident energy. The theoretical curves in each case are the results of a four-state close coupling calculation by Moores and Norcross[15] at an inelastic energy of 4.0 eV, corresponding to 1.9 eV superelastic energy. Though there are significant discrepancies between the theoretical and experimental results, the overall agreement, particularly for the ratio r, is reasonably good over the entire measured angular range. This agreement is very encouraging and indicative of the accuracy of close coupling methods in this low energy range.

It is interesting, however, to further consider the discrepancy at small angles for $L_\perp^S$. This inadequacy of the theory is scarcely noticeable in the unpolarized results shown in Fig. 2(a). The disagreement in the singlet channel is masked in the unpolarized results simply because triplet scattering events are three times more likely than singlet events in an unpolarized experiment. This dramatically illustrates the importance of making measurements that are as complete as possible when striving for the

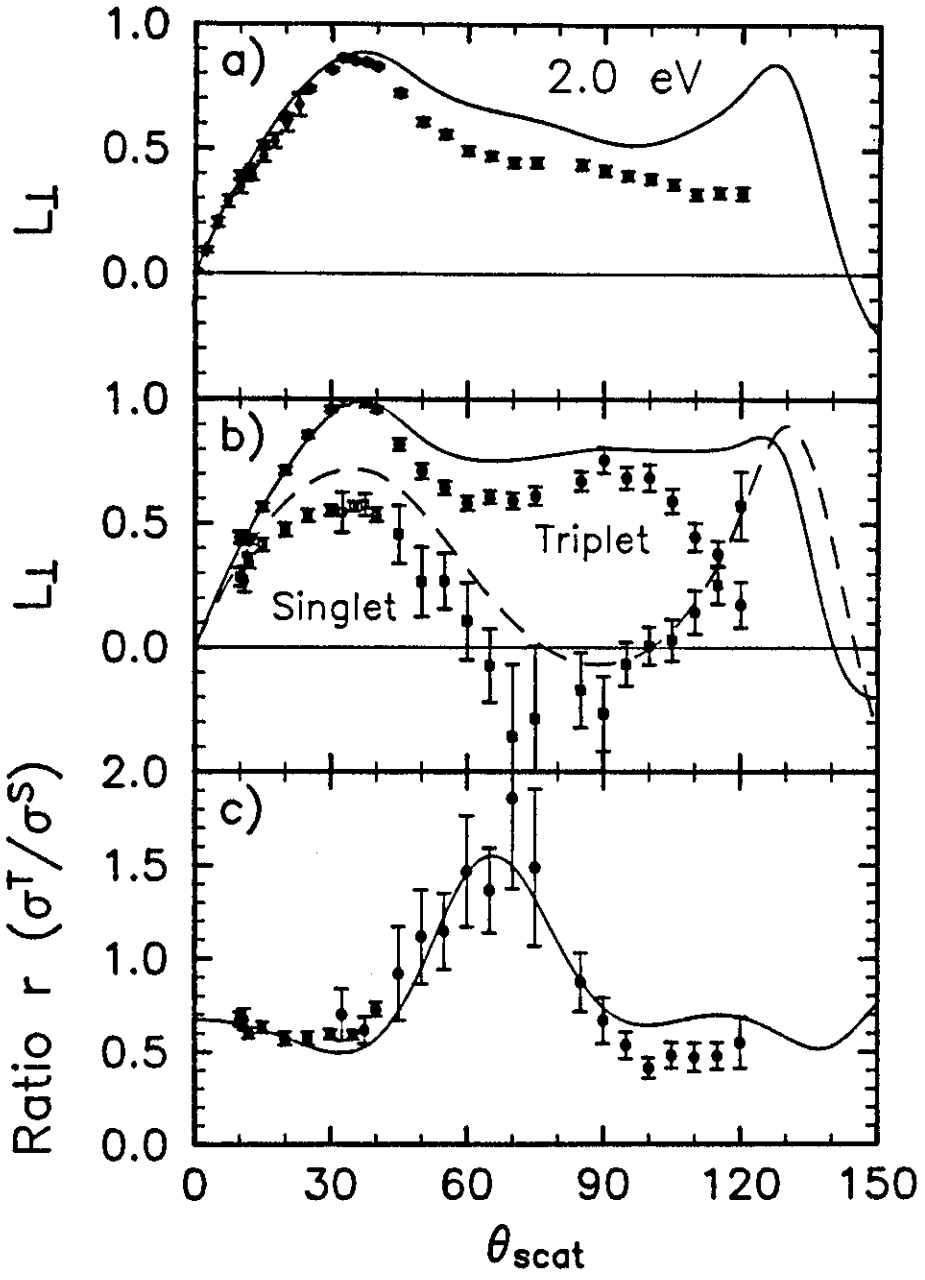

Fig. 2. Spin-polarized superelastic scattering from Na($3P$) at 2 eV incident energy vs. scattering angle θ_{scat}. (a) Unpolarized measurement of angular momentum transferred perpendicular to the scattering plane, $L_\perp$. Solid circles from McClelland *et al.*[12]; Open diamonds from Hermann *et al.*[14] (3 eV incident energy); solid line, four-state close coupling calculation of Moores and Norcross[15]. (b) Singlet (open squares) and triplet (solid circles) perpendicular angular momentum transfer, $L_\perp^S$ and $L_\perp^T$, with calculations of Moores and Norcross[15] (solid and dashed curves). (c) Ratio r of triplet to singlet cross sections. Solid circles from McClelland *et al.*[12]; solid line, theory of Moores and Norcross[15].

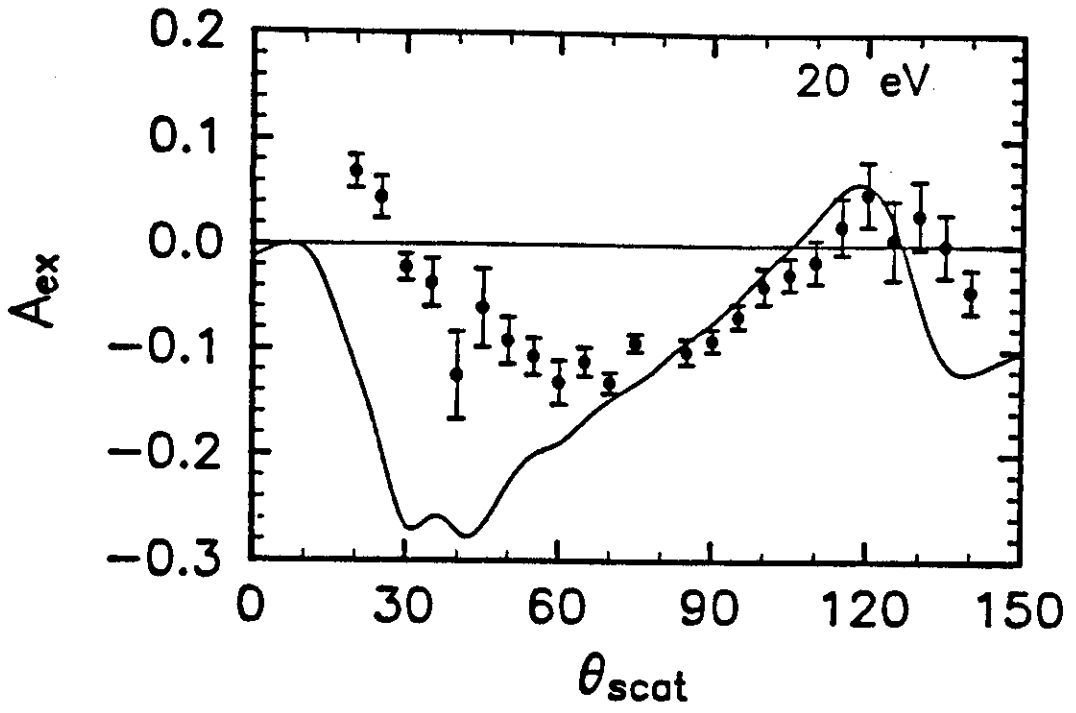

Fig. 3. Exchange asymmetry A_{ex} for elastic scattering from Na at 20.0 eV. Theory is from a four-state close-coupling calculation of Oza[17].

most sensitive possible tests of theoretical predictions.

A recent, but as yet unpublished, seven-state close-coupling calculation by Zhou *et al.*[16] removes essentially all of the discrepancy between the theory and these experimental results. The excellent agreement found for all experimentally determined quantities gives a strong indicator of the reliability of this calculational method for this collision process.

Our results for an incident energy of 20.0 eV, about four times the ionization threshold, are shown in Fig. 3 and Fig. 4. The 17.9 eV energy for superelastic scattering was chosen to correspond to conventional inelastic scattering at 20.0 eV incident energy.

In Fig. 3 is shown the elastic exchange asymmetry A_{ex}, which is related by Eq. (10) to the triplet-to-singlet cross section ratio. It is apparent from the figure that exchange still has an important effect in the elastic scattering channel even at this moderate energy. Over much of the angular range triplet scattering is larger than singlet scattering, by nearly a factor of two in the neighborhood of 60°. At small angles, singlet becomes increasingly more important, dominating by about 30% at 20°.

Also shown in Fig. 3 is the exchange asymmetry from a four-state close coupling calculation of Oza[17]. The agreement between theory and experiment is quite good

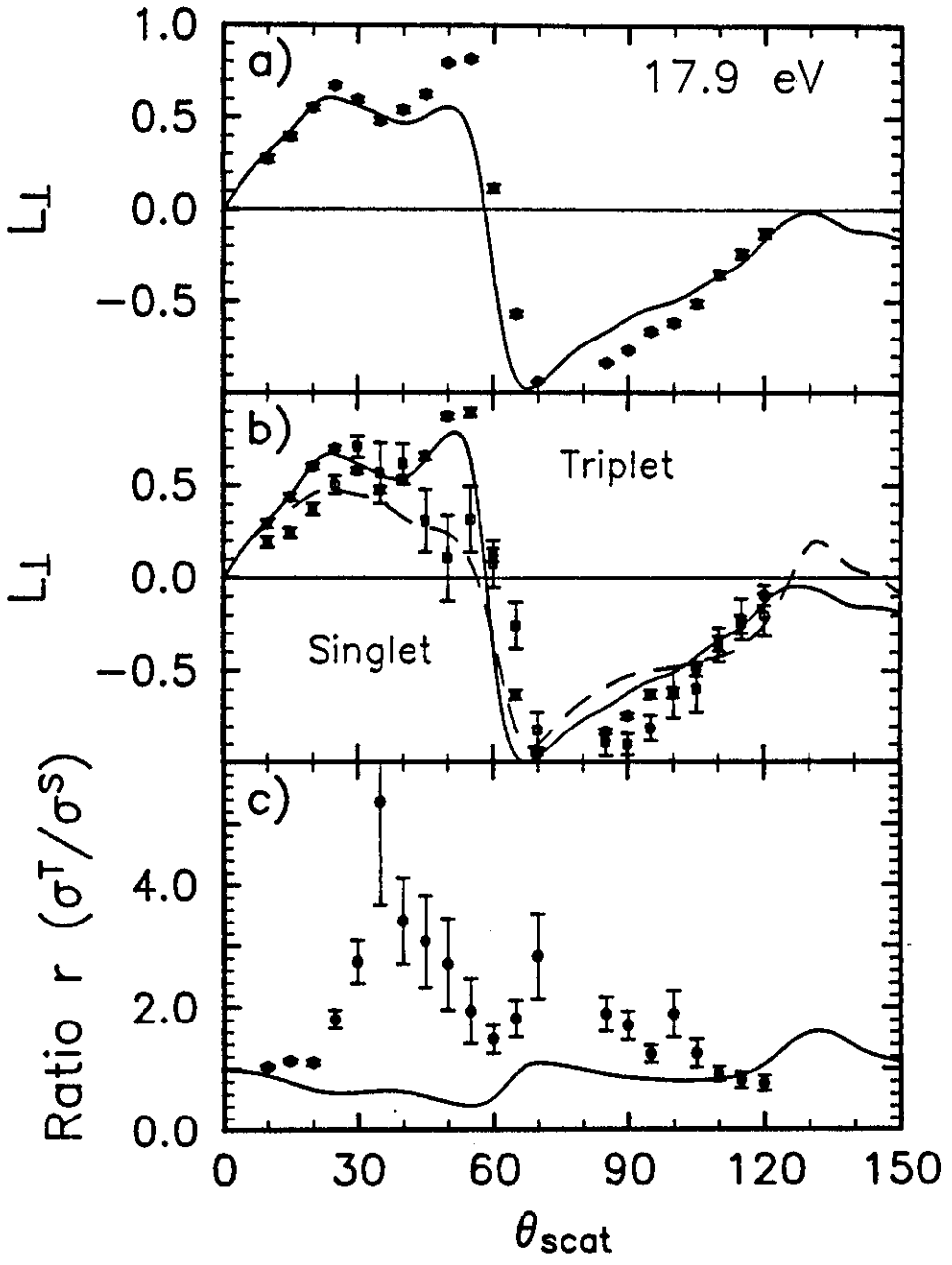

Fig. 4. Spin-polarized superelastic scattering from Na($3P$) at 17.9 eV incident energy vs. scattering angle θ_{scat}. (a) Unpolarized measurement of angular momentum transferred perpendicular to the scattering plane, $L_\perp$. (b) Singlet (open squares) and triplet (solid circles) perpendicular angular momentum transfer, $L_\perp^S$ and $L_\perp^T$. (c) Ratio, r of triplet to singlet cross sections.

at large angles, but a significant discrepancy is apparent at smaller angles. The theory predicts a much stronger dominance of triplet over singlet scattering than is seen in the experiment, with this dominance extending essentially down to 0° scattering angle. The source of this disagreement is not at present understood.

Our superelastic results for an incident energy of 17.9eV are shown in Fig. 4. The unpolarized angular momentum transfer, $L_\perp$, is shown in Fig. 4(a), and the singlet and triplet analogs, $L_\perp^S$ and $L_\perp^T$, are shown in Fig. 4(b). The triplet to singlet ratio, r, is shown in Fig. 4(c). The theoretical curves in all cases are the results of a four-state close-coupling calculation by Mitroy *et al*[18]. As seen from the figure, the theory predicts the angular momentum transfer quite well, but misses the relative importance of singlet and triplet scattering quite severely, indicating that further development of the theory is required.

In summary, we have described how spin polarized electrons can be exploited to investigate very fundamental processes in electron–atom collisions and have presented measurements of spin-dependent elastic and inelastic electron scattering from sodium atoms. These measurements represent a significant step toward the complete measurement of the complex scattering amplitudes which describe the electron–atom collision.

Comparison with theoretical results shows that while the best available electron scattering calculations reproduce many aspects of the experimental results exceedingly well, significant discrepancies still exist which point out remaining deficiencies in the theoretical models. Further theoretical progress will require more of the detailed measurements of scattering processes made possible with the use of state-selective techniques. As one approaches the final goal of complete measurement of the complex scattering amplitudes and phases, it is expected that electron scattering theory will be significantly improved in its predictive utility.

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REFERENCES

[1] J. Slevin, Rep. Prog. Phys. **47**, (1984) 461.

[2] N. Andersen, J.W. Gallagher, and I.V. Hertel, Physics Reports **165**, (1988) 1.

[3] H. Kleinpoppen, In Fundamental Processes of Atomic Dynamics, (Eds. J.S. Briggs, H. Kleinpoppen, and H.O. Lutz), Plenum Press, New York, 1988), p. 393.

[4] W.R. MacGillivray and M.C. Standage, In Coherence in Atomic Collision Physics, (Eds. H.J. Beyer, K. Blum, and R. Hippler), Plenum Press, New York, (1988), p. 103.

[5] J. Kessler, Polarized Electrons, Springer-Verlag, Berlin, (1985), 2nd edition.

[6] G.F. Hanne, In Coherence in Atomic Collision Physics, (Eds. H.J. Beyer, K. Blum, and R. Hippler), Plenum Press, New York, (1988), p. 41.

[7] W. Raith, In Fundamental Processes of Atomic Dynamics, (Eds. J.S. Briggs, H. Kleinpoppen, and H.O. Lutz), Plenum Press, New York, (1988), p. 429.

[8] M.H. Kelley, In Electronic and Atomic Collisions, Invited Papers of ICPEAC XVI (North-Holland, New York, NY, (1989), p. 103.

[9] B. Bederson, Comments At. Mol. Phys. **1**, (1969) 41.

[10] I.V. Hertel, M.H. Kelley, and J.J. McClelland, Z. Phys. D **6**, (1987) 163.

[11] I.V. Hertel and W. Stoll, In Advances in Atomic and Molecular Physics, Vol. 13, (Eds. D.R. Bates and B. Bederson), Academic Press, New York, (1978), p. 113.

[12] J.J. McClelland, M.H. Kelley, and R.J. Celotta, Phys. Rev. A **40**, (1989) 2321.

[13] D.T. Pierce, R.J. Celotta, G.-C Wang, W.N. Unertl, A. Galejs, C.E. Kuyatt, and S.R. Mielczarek, Rev. Sci. Instrum. **51**, (1980) 478.

[14] H.W. Hermann, I.V. Hertel, and M.H. Kelley, J. Phys. B: At. Mol. Phys. **13**, (1980) 3465.

[15] D.L. Moores and D.W. Norcross, J. Phys. B: At. Mol. Phys. **5**, (1972) 1482.

[16] H.L. Zhou, B.L. Whitten, and D.W. Norcross, private communication.

[17] Dipak H. Oza, Phys. Rev. A **37**, (1988) 2721.

[18] J. Mitroy, I.E. McCarthy, and A.T. Stelbovics, J. Phys. B: At. Mol. Phys. **20**, (1987) 4827.